

RESEARCH ARTICLE

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Special Section:

Space Weather Events of 4–10 September 2017

Key Points:

- GCR radiation doses are rising faster than predicted previously
- SEP radiation events are large despite low solar activity
- Radiation environment is a significant factor for mission planning

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# Update on the Worsening Particle Radiation Environment Observed by CRaTER and Implications for Future Human Deep-Space Exploration

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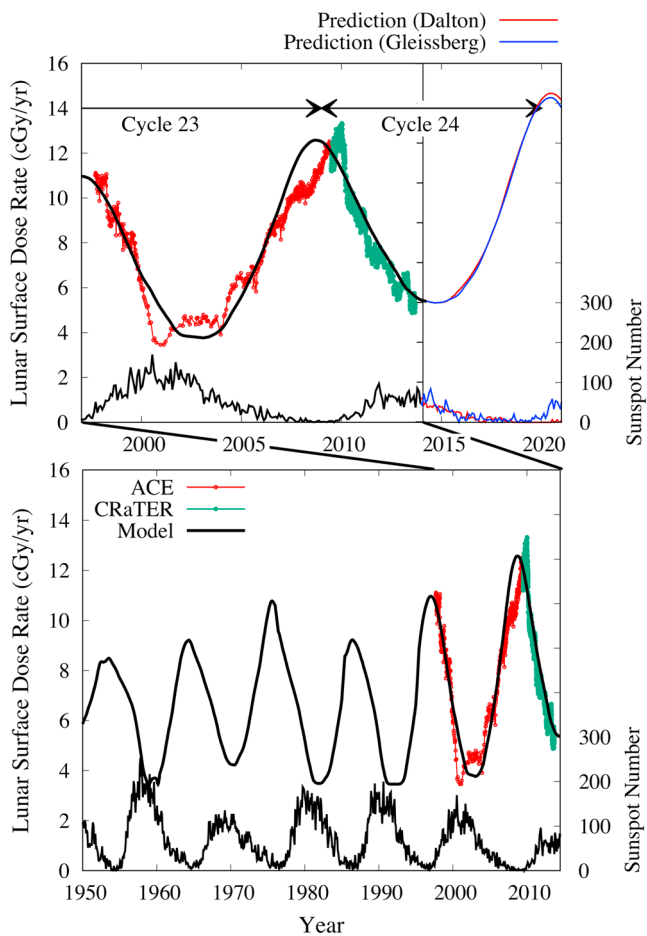
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**Abstract** Over the last decade, the solar wind has exhibited low densities and magnetic field strengths, representing anomalous states that have never been observed during the space age. As discussed by Schwadron, Blake, et al. (2014, <https://doi.org/10.1002/2014SW001084>), the cycle 23–24 solar activity led to the longest solar minimum in more than 80 years and continued into the “mini” solar maximum of cycle 24. During this weak activity, we observed galactic cosmic ray fluxes that exceeded the observed small solar energetic particle events. Here we provide an update to the Schwadron, Blake, et al. (2014, <https://doi.org/10.1002/2014SW001084>) observations from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter. The Schwadron, Blake, et al. (2014, <https://doi.org/10.1002/2014SW001084>) study examined the evolution of the interplanetary magnetic field and utilized a previously published study by Goelzer et al. (2013, <https://doi.org/10.1002/2013JJA019404>) projecting out the interplanetary magnetic field strength based on the evolution of sunspots as a proxy for the rate that the Sun releases coronal mass ejections. This led to a projection of dose rates from galactic cosmic rays on the lunar surface, which suggested a ~20% increase of dose rates from one solar minimum to the next and indicated that the radiation environment in space may be a worsening factor important for consideration in future planning of human space exploration. We compare the predictions of Schwadron, Blake, et al. (2014, <https://doi.org/10.1002/2014SW001084>) with the actual dose rates observed by CRaTER in the last 4 years. The observed dose rates exceed the predictions by ~10%, showing that the radiation environment is worsening more rapidly than previously estimated. Much of this increase is attributable to relatively low-energy ions, which can be effectively shielded. Despite the continued paucity of solar activity, one of the hardest solar events in almost a decade occurred in September 2017 after more than a year of all-clear periods. These particle radiation conditions present important issues that must be carefully studied and accounted for in the planning and design of future missions (to the Moon, Mars, asteroids, and beyond).

**Plain Language Summary** We examine the evolution of fluxes from galactic cosmic rays and recent solar energetic particle events to evaluate the recent evolution of radiation hazards in space and their implications for human and robotic exploration.

## 1. Introduction

Galactic cosmic rays (GCRs) and solar energetic particles (SEPs) pose significant challenges to long-duration crewed missions to deep space. The human biological consequences of particle radiation range from acute effects (radiation sickness) to long-term effects (cf. NRC, 2008) including cancer induction and organ damage (including the heart, brain, and central nervous system). Risks associated with radiation hazards are typically



**Figure 1.** Evolving and increasingly hazardous radiation levels in space. (top) Advanced Composition Explorer (ACE) dose rates (red) are based on fits to Cosmic Ray Isotope Spectrometer spectra (O'Neill, 2006); Cosmic Ray Telescope for the Effects of Radiation (CRaTER) measurements (green) from the zenith facing D1/D2 detectors are used as proxies for lens dose rates behind 0.3 g/cm<sup>2</sup> Al shielding (Schwadron et al., 2012). The sunspot number predictions (the lower blue and red dashed lines) show two cases based on a Gleissberg-like and a Dalton-like minimum, the results of which are similar. The dose predictions (solid black curve and the upper blue and red curves) are from a sunspot-based model of the heliospheric magnetic field and the correlated variation in modulation of galactic cosmic rays (Schwadron, Blake, et al., 2014, Appendix A). The ACE data, CRaTER data, and model results are projected to the lunar surface. (bottom) Same as top panel but for a longer time span (from Schwadron, Blake, et al., 2014).

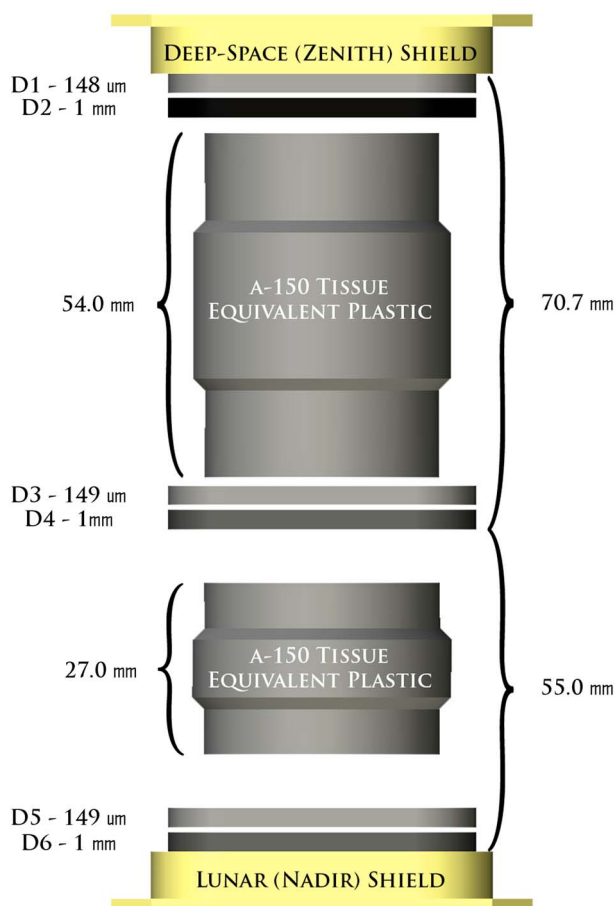
quantified as a function of the effective dose that is related to the energy per unit mass (expressed in Gy = J/kg) absorbed by biological tissue and weighted according to the effectiveness of radiation damage in biological tissue. In this paper, we use recent measurements from the CRaTER instrument (Cosmic Ray Telescope for the Effects of Radiation, Spence et al., 2010) on the Lunar Reconnaissance Orbiter (LRO) to determine dose rates (data available at <http://prediccs.sr.unh.edu/craterweb>).

The deep solar cycle 23–24 minimum and the activity that followed in cycle 24 differed significantly from those of the prior solar cycles during the space age (McComas et al., 2013; Schwadron et al., 2011; Schwadron, Goelzer et al., 2014). Most recently, Rahmanifard et al. (2017) concluded that we may be entering an era of extremely low solar activity, such as a Dalton minimum, a Gleissberg minimum, or a Maunder Minimum. Specifically, Rahmanifard et al. (2017) studied the recent trends in the evolution of the heliospheric magnetic field (HMF) in the context of past solar grand minima, especially the Maunder period (1645–1715) to gain further insight. A time series of the HMF was reconstructed from geomagnetic data and measurements from near-Earth spacecraft (OMNI) to find the timescales that control heliospheric field evolution through conversion from coronal mass ejections (CMEs) into the ambient field, removal of the ambient field through magnetic reconnection, and interchange reconnection between CME and ambient magnetic flux. The minimum value for the HMF at 1 au in the reconstructed magnetic field is  $3.13 \pm 0.35$  nT (Rahmanifard et al., 2017), which is  $\sim 1$  nT lower than observed in the deep cycle 23–24 minimum. Therefore, the analysis of Rahmanifard et al. (2017) suggests that while we have already observed significant weakening in solar activity, there exists the potential for far weaker activity in coming cycles.

Schwadron, Blake, et al. (2014) examined the radiation environment utilizing data from CRaTER and from PREDICCS (Predictions of Radiation from RELeASE, EMMREM, and Data Incorporating the CRaTER, COSTEP, and other SEP measurements, <http://prediccs.sr.unh.edu> Schwadron, 2012). PREDICCS provides for nowcasting the radiation environment near Earth, at the Moon, and near Mars. Figure 1 shows a key result of Schwadron, Blake, et al. (2014) indicating that dose rates (projected to the lunar surface) have grown in the last solar minimum to the highest level observed in the space age. A second major conclusion in Schwadron, Blake, et al. (2014) is that SEP events have been quite weak during solar cycle 24. The probability of a SEP event exceeding either the 30 day or 1 year blood-forming organ limits is vanishingly small for deep-space mission with at least 10 g/cm<sup>2</sup> shielding up to 1 year.

Schwadron, Blake, et al. (2014) were able to make a prediction for the evolution of the radiation environment on the lunar surface slightly beyond 2020. The basis of this prediction was the results of Goelzer et al. (2013), in which projections for the interplanetary magnetic field strength were made based on similarity of the solar cycle progression to the Dalton and Gleissberg minima. As seen in Figure 1, both projections showed that GCR dose rates in the coming solar minimum between cycles 24 and 25 will be significantly higher ( $\sim 20\%$ ) than the previous solar minimum. This results in a  $\sim 20\%$  reduction in the time to reach a given level of risk of exposure-induced death for astronauts in interplanetary space. These findings show the pressing need to improve upon the understanding of the space radiation risk, predict likely clinical outcomes of interplanetary radiation exposure, and develop appropriate and effective mitigation strategies for future missions.

The purpose of this paper is to revisit the predictions of Schwadron, Blake, et al. (2014) with the benefit of 3.5 years of additional CRaTER data. In the discussion of weakening solar activity, we provide data on one



**Figure 2.** The Cosmic Ray Telescope for the Effects of Radiation instrument consists of a stack of three pairs of thin and thick silicon detectors separated by tissue-equivalent plastic. Shown here is the configuration of these detectors with D1-D2 facing zenith and D5-D6 facing in the nadir direction. Note that the D3-D4 detectors are the most shielded thin-thick pair within the instrument.

of the largest SEP events of solar cycle 24 during September 2017. Our paper is therefore included in the *Space Weather* special section, “Space Weather Events of 4–10 September 2017.” The paper is organized as follows: section 2 describes the CRaTER; section 3 describes the radiation environment due to evolving galactic cosmic fluxes; section 4 describes the dose rates and accumulated doses observed during the September 2017 SEP event; section 5 describes interplanetary conditions near 1 au and modeling showing the configuration of successive CMEs giving rise to the September 2017 SEP event; and section 6 provides conclusions.

## 2. Cosmic Ray Telescope for the Effects of Radiation

The CRaTER instrument consists of a linear stack of three pairs of thin and thick silicon detectors, labeled D1 through D6 (Spence et al., 2010) (Figure 2). With CRaTER in its typical orientation, D1-D2 face deep space, and the thin-thick detector pair D5-D6 faces the Moon. In this orientation, energetic particles originating from the zenith pass through (1) 0.81 mm (0.22 g/cm<sup>2</sup>) Al endcap, (2) D1-D2 detectors, (3) tissue-equivalent plastic (TEP) of thickness 54 mm (6.09 g/cm<sup>2</sup>), (4) D3-D4 detectors, (5) 27 mm (3.04 g/cm<sup>2</sup>) TEP, (6) D5-D6 detectors, and (7) 0.81 mm (0.22 g/cm<sup>2</sup>) Al endcap. Further details on CRaTER can be found in Spence et al. (2010). Significant energy loss occurs within the TEP. Therefore, D3-D4 are the most shielded detectors within the instrument.

The energy loss within the TEP allows us to differentiate between particles coming from the Moon and GCRs from deep space at energies below a few hundred MeV/nuc. As a particle traverses the detector stack, it loses energy, primarily within the TEP. Lower-energy particles deposit more energy in a detector than higher-energy particles. As a result, a coincident event that is registered in both D4 and D6 (both thick detectors) typically deposits a greater amount of energy in D4 than in D6 if it originates from the direction of the Moon. Conversely, if the particle originates from deep space, it will deposit a greater amount of energy in D6 than in D4, although at high energies, signals in the two detectors are indistinguishable. Note that the coincident rates in D4 and D6 from GCRs are larger than the coincident rates in D2 and D4 due to the larger field of view and the

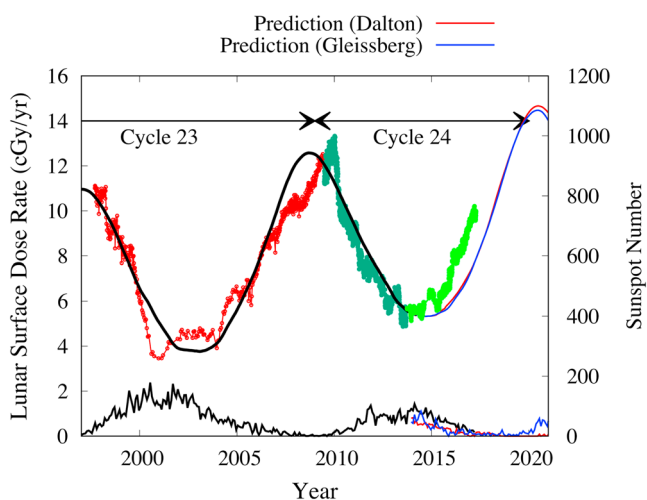
comparatively small energy loss within the TEP between D4 and D6 (the piece of TEP between D2 and D4 is thicker than the piece between D4 and D6).

The microdosimeter housed within CRaTER is an early version of what is now a commercially available hybrid that accurately measures total ionizing radiation dose in a silicon target (<http://www.teledynemicro.com/product/radiationdosimeter>). The CRaTER microdosimeter is behind about ~4.4 g/cm<sup>2</sup> equivalent aluminum, which shields against protons below ~55 MeV. Mazur et al. (2011) discussed the first 6 months of mission data from the microdosimeter, and Mazur et al. (2015) updated the microdosimeter data from the start of the LRO mission through the end of 2014.

As in Schwadron et al. (2012) we correct the observed dose rate for the changing solid angle blocked by the Moon and for the difference in energy deposition in water/tissue versus silicon. All dose rates and accumulated doses are adjusted to the lunar surface, where half of the sky is blocked by the Moon. When averaged over 12 h, the variations among the various orbit modes have less than a 5% and 20% effect on the GCR dose rate and peak solar proton dose rate, respectively.

## 3. Does the Galactic Radiation Hazard Continue to Worsen?

We test the predictions from Schwadron, Blake, et al. (2014) with new CRaTER data from 2014 to 2017 (Figure 3, bright green). As detailed by Schwadron, Blake, et al. (2014), the measurements of Advanced Composition



**Figure 3.** Recent Cosmic Ray Telescope for the Effects of Radiation (CRaTER) data (bright green) are updated after the Schwadron, Blake, et al. (2014) study to further test the predictions. The sunspot number predictions from Goelzer et al. (2013) (the lower blue and red curves) show two cases based on a Gleissberg-like and a Dalton-like minimum, the results of which are similar. Updates to the sunspot number (lower black curve) are adapted from the international sunspot number released by Sunspot Index and Long-term Solar Observations (<http://sidc.oma.be/silso/home>). The dose predictions (solid black curve and the upper red and blue curves) are from a sunspot-based model of the heliospheric magnetic field and the correlated variation in modulation of galactic cosmic rays (Schwadron, Blake, et al., 2014, Appendix A). The Advanced Composition Explorer data, CRaTER data, and model results are projected geometrically to the lunar surface.

Explorer (ACE) in Figure 3 (red) result from fitting heavy ion distributions measured by ACE/CRIS (Stone et al., 1998) to a model (O'Neill, 2006) for GCR distributions, which are then fed in to HZETRN 2005 to estimate associated dose rate. The data from ACE are provided up to 2010, after which we use dose rates measured by CRaTER (dark green points show CRaTER data published previously; light green points show more recent data).

Model results are shown in Figure 3 (black curves prior to 2014, and blue and red curves after 2014) (Schwadron, Blake, et al., 2014). Sunspot numbers (SSNs) are used as a proxy for CME frequency (number of CMEs ejected per unit time). The ejection of successive CMEs introduces new magnetic flux into the heliosphere, thereby increasing the magnitude of the HMF. The low solar activity of the minimum between cycles 23 and 24 enabled steady disconnection of magnetic flux unbalanced by the addition of new magnetic flux from CMEs (Connick et al., 2009). The low heliospheric magnetic flux reduces the modulation of GCRs and increases GCR fluxes. The dose rates shown in Figure 1 are therefore higher during the 2008–2009 activity lull compared to the 1997 solar minimum, and the mini-maximum in cycle 24 continues to show relatively weak solar activity.

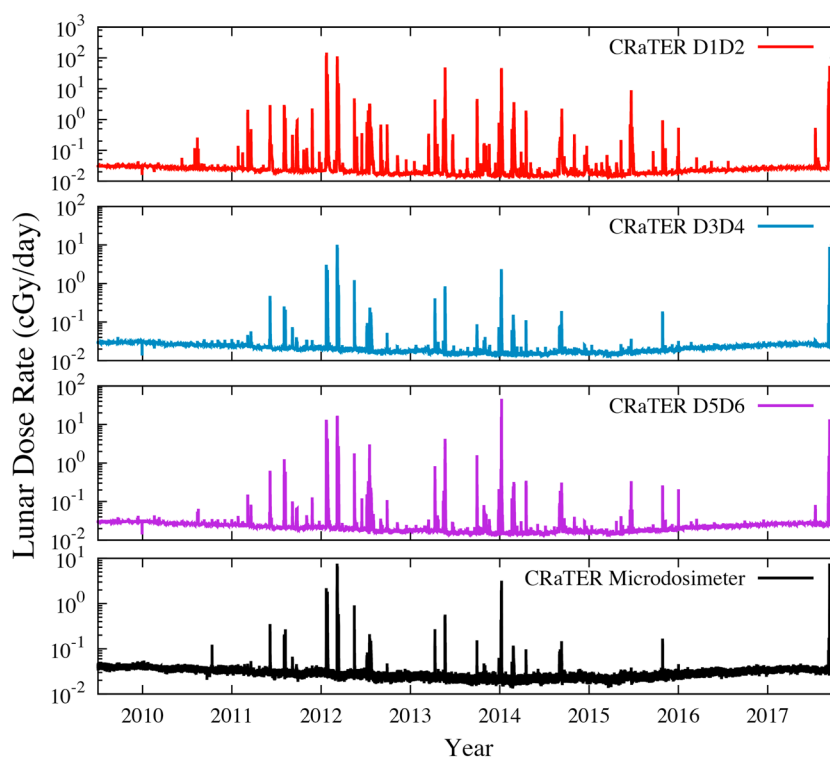
(Goelzer et al., 2013) showed that recent trends are consistent with the beginning of the 1790–1830 period (the Dalton minimum) or the beginning of the 1890–1920 period (the Gleissberg minimum) (Smith et al., 2014). Solar activity over the next ~ 5 years (through 2020) was estimated (Goelzer et al., 2013; Smith et al., 2014) based on the historic behavior in sunspot evolution for the Dalton-like minimum and the Gleissberg-like minimum. Recent CRaTER data (bright green points)

obtained after the Schwadron, Blake, et al. (2014) study are compared to predictions in Figure 3. The CRaTER observations are enhanced relative to the predictions by ~ 10%, demonstrating an even more rapid increase in radiation dose rates than associated with a Dalton-like or a Gleissberg-like minimum.

Cosmic ray drifts are known to influence the time evolution of GCR fluxes (Jokipii et al., 1977). The cosmic ray drift patterns depend on the quantity  $qA$ , where  $q$  is the cosmic ray charge and the sign of  $A$  corresponds to the dominant polarity of the northern HMF. In cycles with  $qA > 0$ , cosmic rays drift inward near the poles and outward near the heliospheric current sheet. In these cycles, we typically observe “flat-topped” maxima in the time evolution of GCR fluxes. In contrast, cycles with  $qA < 0$  have cosmic ray drift patterns outward near the poles and inward near the current sheet causing “peaked” maxima in the time evolution of GCR fluxes (Smith, 1990; Webber & Lockwood, 1988). For protons and cosmic rays with  $q > 0$ , which contribute most of the GCR dose, the solar minimum between cycles 23 and 24 had  $qA < 0$  and a peaked maximum in GCR flux, whereas the solar minimum between cycle 24 and 25 will have  $qA > 0$  and a flat-topped maximum. The more rapid increase in dose rate reported here could be influenced by the change in cosmic ray drift patterns in the transition to the cycle 24–25 solar minimum. For this reason, it will be important to compare the shape of the maximum in dose rates observed by CRaTER in the time frame of 2020 (the cycle 24–25 GCR flux maximum) with the peaked maximum previously observed in 2009 (the cycle 23–24 GCR flux maximum).

While these observations suggest the evolution toward a grand minimum, it is important to bear in mind that various solar activity models yield disparate predictions, due to a lack of understanding of the underlying mechanisms that drive solar activity. For example, in contrast to the prediction of a prolonged deep minimum, a model based on observations of the solar polar magnetic fields near solar minimum (Svalgaard, 2017) predicts that the cycle 25 maximum will be stronger than the cycle 24 maximum; this model accurately predicted the weak cycle 24 maximum (Svalgaard et al., 2005). Another well-known model (Hathaway & Upton, 2016) predicts that the cycle 25 maximum will be about the same as that of cycle 24. Neither of these scenarios is consistent with the onset of a grand minimum.

We also show an update for the SSNs (black curve) in Figure 3 based on the international SSN released by Sunspot Index and Long-term Solar Observations (SILSO, <http://sidc.oma.be/silso/home>). In our 2014 paper



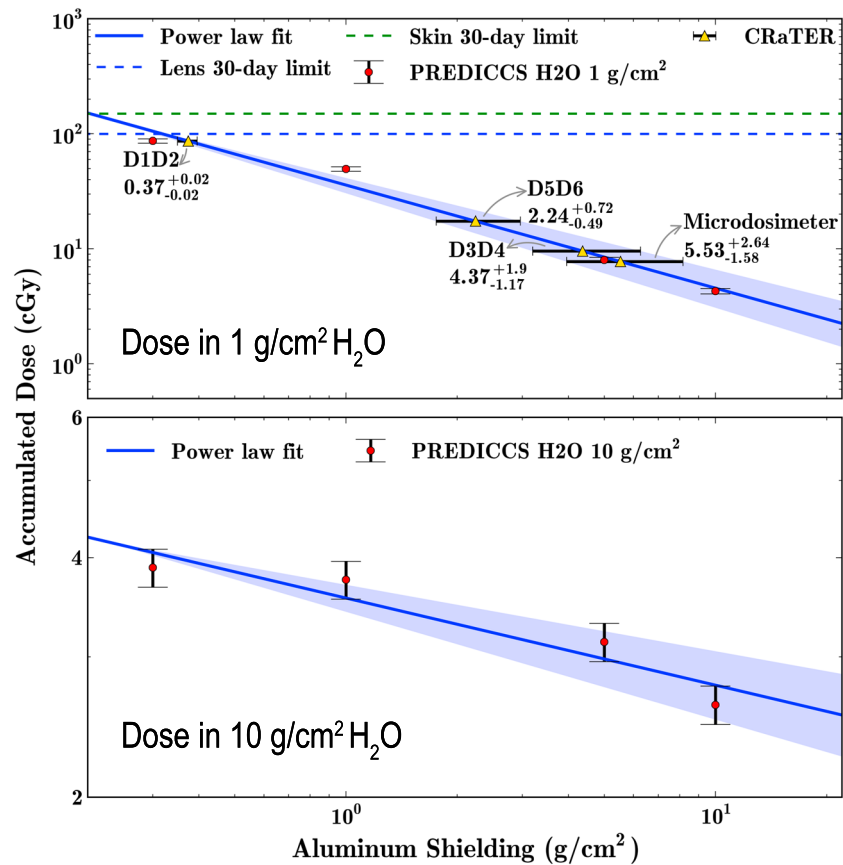
**Figure 4.** Dose rates in the three thin-thick detector pairs (D1-D2, D3-D4, and D5-D6) and the microdosimeter within the Cosmic Ray Telescope for the Effects of Radiation (CRaTER). All dose rates have been geometrically corrected for exposure on the lunar surface and corrected for doses in H<sub>2</sub>O as opposed to Si (Schwadron et al., 2012).

we used the original international SSN, which has been updated since then to remove the conventional Zurich factor (0.6) and eliminate the effect of a new counting method applied in Zurich by reducing all numbers after 1947 by 18% (<http://sidc.oma.be/press/01/welcome.html>). Since in our work we use SSN as a proxy for the solar activity, we are primarily focused on the variations in SSN. In order to be consistent with our previous paper, we adapt the new SSN data set from SILSO for equivalent SSNs.

Recently, Rahmanifard et al. (2017) investigated the rate of CMEs from Large Angle and Spectrometric Coronagraph (LASCO) and performed a chi-square analysis to derive the relationship between SSN and CME rate. This analysis resulted in lower CME rate than used by Goelzer et al. (2013) and therefore an update to the modulation model developed by Schwadron, Blake, et al. (2014).

The minimum dose rate in Figure 3 near the end of 2014 is similar to the minimum dose rate observed, which is ~40% higher in cycle 24 as compared to cycle 23. This is important both because of the large increase in dose rate and because the inflection in dose rate is now observed by CRaTER with the addition of new data. The fact that the observed dose rates exceed the model prediction demonstrates that the paucity of solar activity continues to cause elevated cosmic ray fluxes and higher dose rates at this phase of the solar cycle than observed previously in the space age.

Modulation of GCRs by the interplanetary magnetic field is a stochastic process, and the relationship between a given level of activity and the resulting flux in the inner heliosphere is nontrivial. However, broadly speaking, modulation shifts the energy of ions in the local interstellar spectrum to lower energies and depletes the low-energy portion of the spectrum. During periods of weak modulation, fluxes of relatively low-energy ions (with kinetic energies below about 1 GeV/nuc) are enhanced compared to periods of strong modulation, but a significant share of these ions have ranges that are insufficient to penetrate moderate depths of shielding. This is particularly true for high-charge ions due to the  $Z^2$  dependence of ionization energy loss, and these ions contribute significantly to dose in free space or under thin shielding. Less dramatic increases in dose rates are seen when shielding is more substantial. For example, the NASA OLTARIS model Singletery et al. (2011)



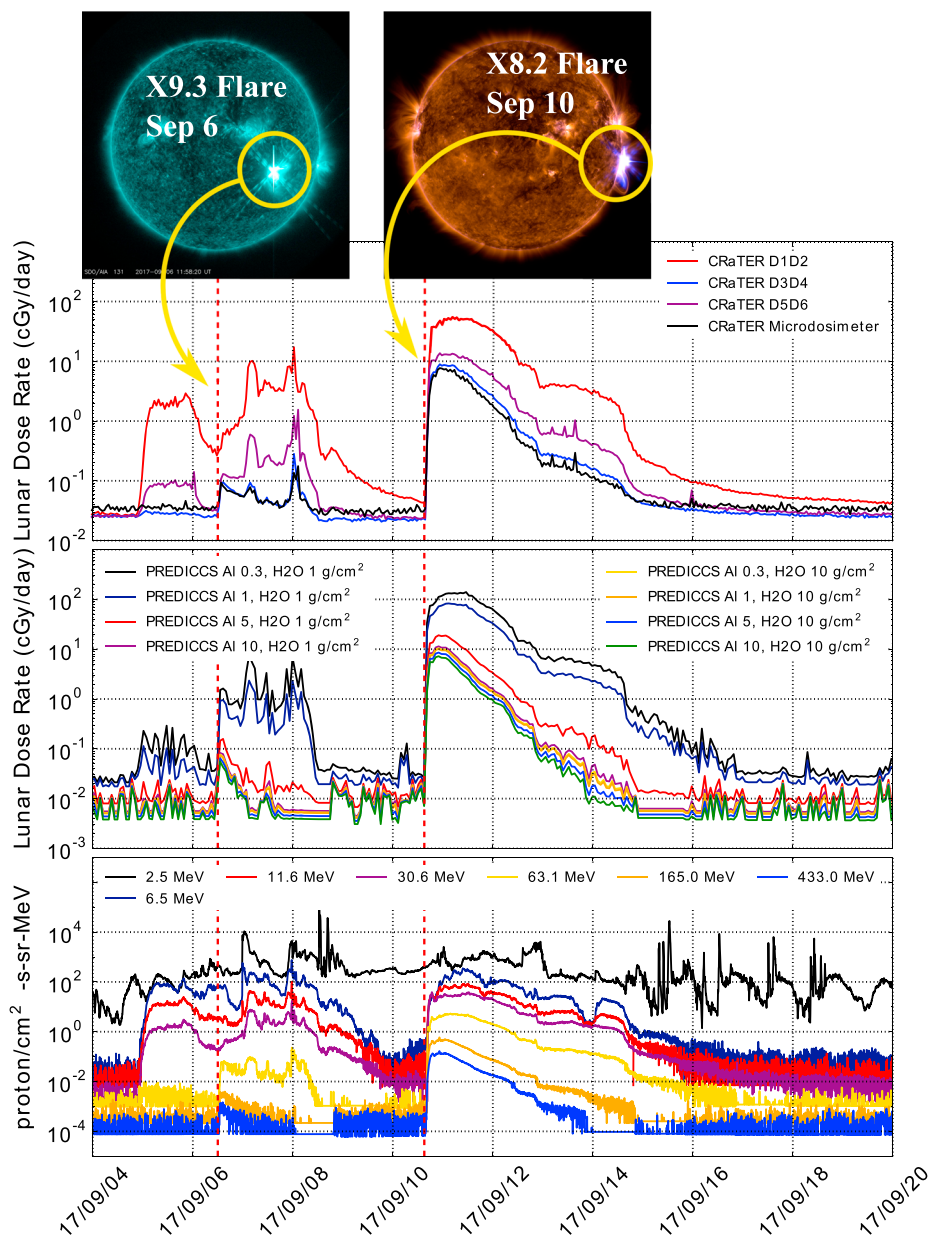
**Figure 5.** Accumulated doses on the lunar surface during the September 2017 solar energetic particle event behind different amounts of Al shielding. Red data points show Predictions of Radiation from REleASE, EMMREM, and Data Incorporating the CRaTER, COSTEP, and other SEP measurements (PREDICCS) data including uncertainties. The blue line and shaded uncertainty region shows power law fit to the PREDICCS data,  $D = D_0(s/s_0)^\gamma$ , where  $D$  is dose,  $s$  is Al shielding thickness, and  $s_0 = 1 \text{ g/cm}^2$ . The fits have the following coefficients: (top)  $D_0 = 35.91 \pm 5.45 \text{ cGy}$ ,  $\gamma = -0.90 \pm 0.10$ , (bottom)  $D_0 = 3.56 \pm 0.14 \text{ cGy}$ ,  $\gamma = -0.11 \pm 0.03$ . In the top panel, we find the accumulated doses for D1-D2, D3-D4, and D5-D6 and the intersection with the power law fit to estimate the effective shielding for each of these Cosmic Ray Telescope for the Effects of Radiation (CRaTER) thin-thick detector pairs. The numbers and uncertainties next to the thin-thick detector pairs indicate effective Al shielding depth (in  $\text{g/cm}^2$ ). In the bottom panel, we show PREDICCS data and the power law fit for doses in  $10 \text{ g/cm}^2 \text{ H}_2\text{O}$ . Note that CRaTER detector pair dose rates are comparable to doses in the lens and skin ( $\sim 1 \text{ g/cm}^2$  of  $\text{H}_2\text{O}$  as a proxy). However, the tissue-equivalent plastic between D1-D2 and D3-D4 is  $\sim 6.09 \text{ g/cm}^2$  and therefore not sufficiently thick to evaluate the large internal mass ( $\sim 10 \text{ g/cm}^2$  of  $\text{H}_2\text{O}$  as a proxy) associated with organ and blood-forming organ doses. Therefore, the lower panel includes only PREDICCS data and the power law fit but does not contain CRaTER data.

predicts that  $30 \text{ g cm}^{-2}$  of aluminum shielding produces a roughly 10% decrease in dose rate for solar minimum conditions and a roughly 15% increase under solar maximum conditions, tending to blunt the changes in the incident GCR fluxes.

#### 4. The SEP Hazard During Periods of Weak Activity

Schwadron, Blake, et al. (2014) studied the probability of SEP events using PREDICCS (Schwadron, 2012). They found that the probability of reaching the 30 day blood-forming organ dose limit of 25 cGy-equivalent behind  $10 \text{ g/cm}^2$  aluminum shielding was insignificant over timescales of 30 days to 1 year (NRC, 2008).

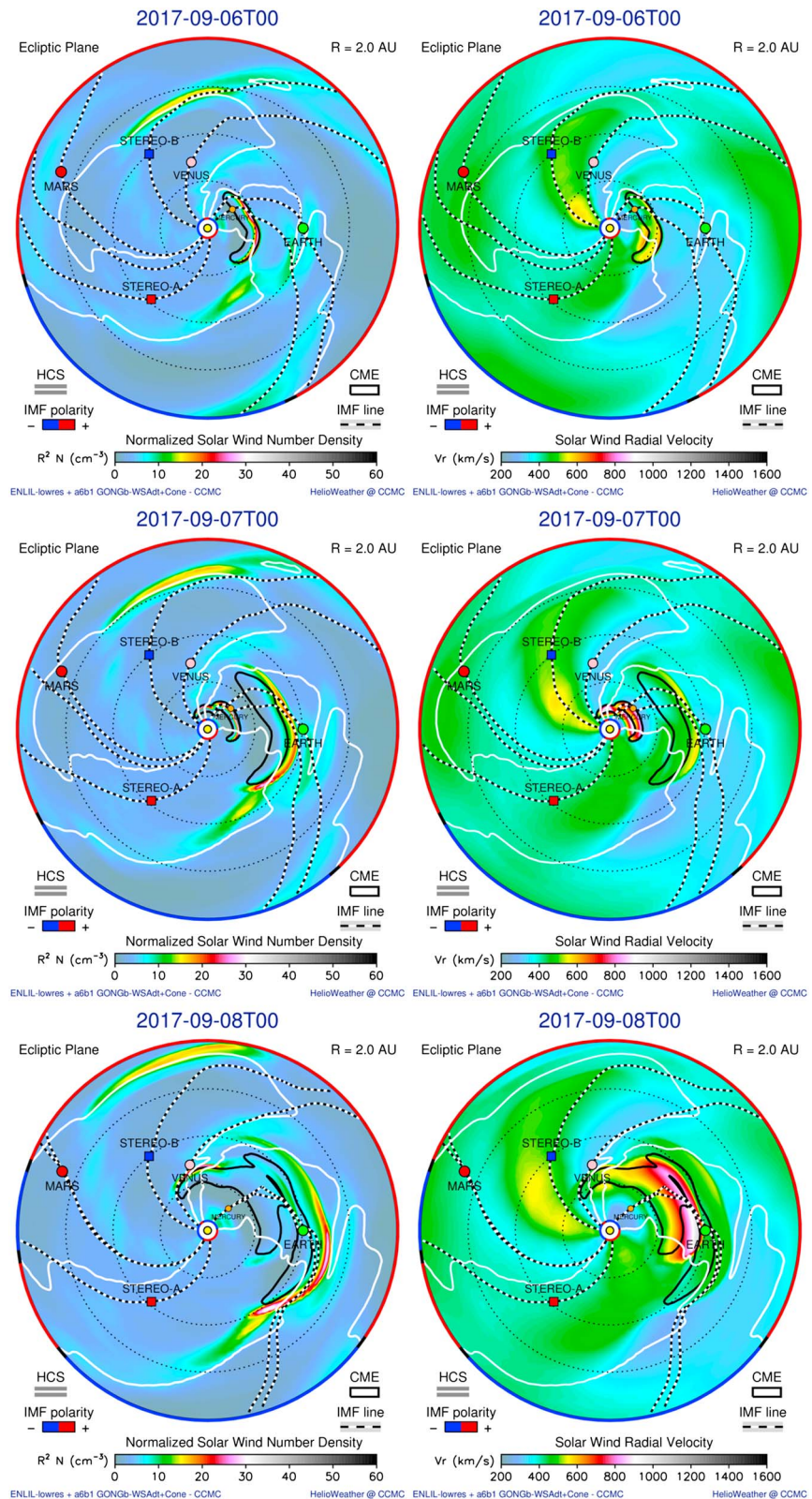
While the cycle 24 conditions indicate a low probability for an extreme event, the recent 10 September 2017 SEP event demonstrates that large events can arise with little warning. Figure 4 shows the dose rates in the D1-D2, D3-D4, and D5-D6 detectors and CRaTER microdosimeter; the  $> 1.5$  year lull in activity in 2016–2017 is obvious. The recent September 2017 event was one of the largest of the CRaTER mission and was rivaled only by the March 13 2012 SEP event in terms of the most shielded D3-D4 and microdosimeter dose rates.



**Figure 6.** Large X-class flares began each of the major events observed in September 2017. The first row includes observations of the erupting active region observed by the Solar Dynamics Observatory (SDO), courtesy of NASA/SDO and the Atmospheric Imaging Assembly (AIA), Extreme Ultraviolet Variability Experiment (EVE), and Helioseismic and Magnetic Imager (HMI) science teams. The first row, left panel solar image of the 6 September X9.3 flare (11:58 UT) is from telescope AIA 131. The first row, right panel image of the 10 September X8.2 flare (16:06) is a combination of wavelengths that includes AIA 193. Dose rates on the lunar surface from Cosmic Ray Telescope for the Effects of Radiation (CRaTER) and Predictions of Radiation (PREDICCS) from REleASE, EMMREM, and Data Incorporating the CRaTER, COSTEP, and other SEP measurements (PREDICCS) (third panel) are shown throughout both events. Note that dose rates in free space are approximately 2 times those on the lunar surface. In the fourth panel, we show energetic particle differential fluxes from GOES.

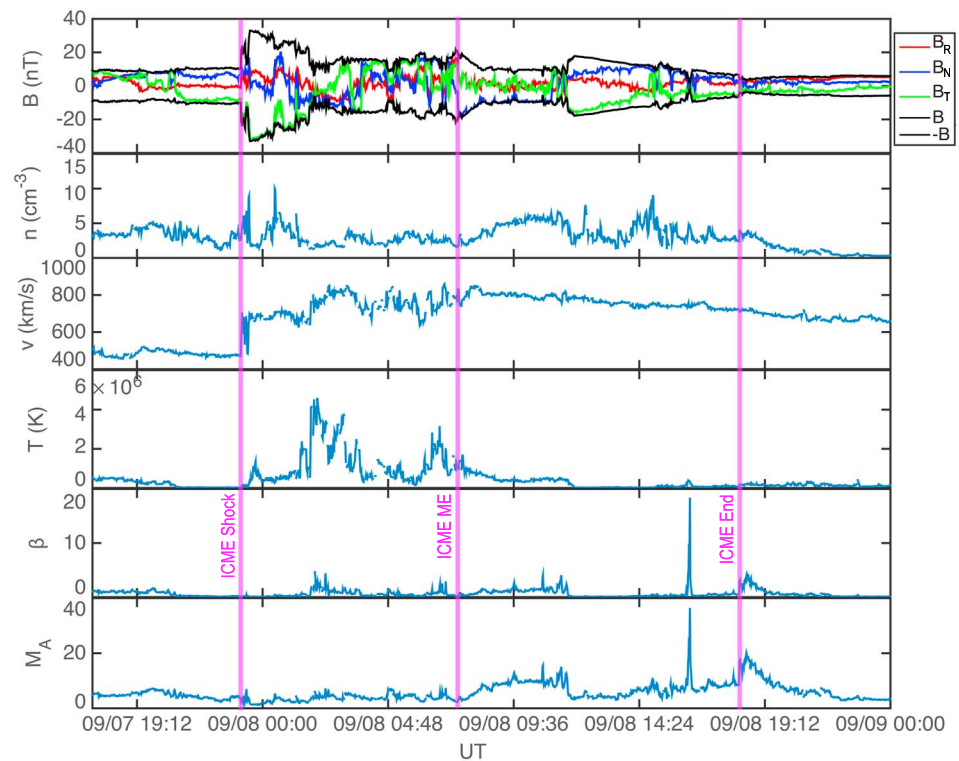
The September 2017 event had an unusually hard spectrum, with large fluxes above 400 MeV, and large dose rates in the most shielded CRaTER detectors. Figure 5 shows the accumulated dose during the event as a function of location and shielding in the CRaTER detector stack accumulated during the event along with the PREDICCS doses modeled through the event into 1 g/cm<sup>2</sup> H<sub>2</sub>O, a proxy for a lens or skin dose.

In Figure 5, we combined CRaTER observations (yellow triangles) with data from PREDICCS (red points). The blue line and shaded uncertainty region represents a power law fit to the PREDICCS data. The functional



**Figure 7.** Propagation of interplanetary coronal mass ejections (ICMEs) from 6 to 8 September 2017 based on Wang-Sheeley-Argé (WSA)-ENLIL simulations. These coronal mass ejections (CMEs) followed the X9.3 flare event on 6 September. The ICMEs over this period propagate toward Earth, and a strong compression region swept past Earth on 7 September. These runs were performed by the Community Coordinated Modeling Center (CCMC).





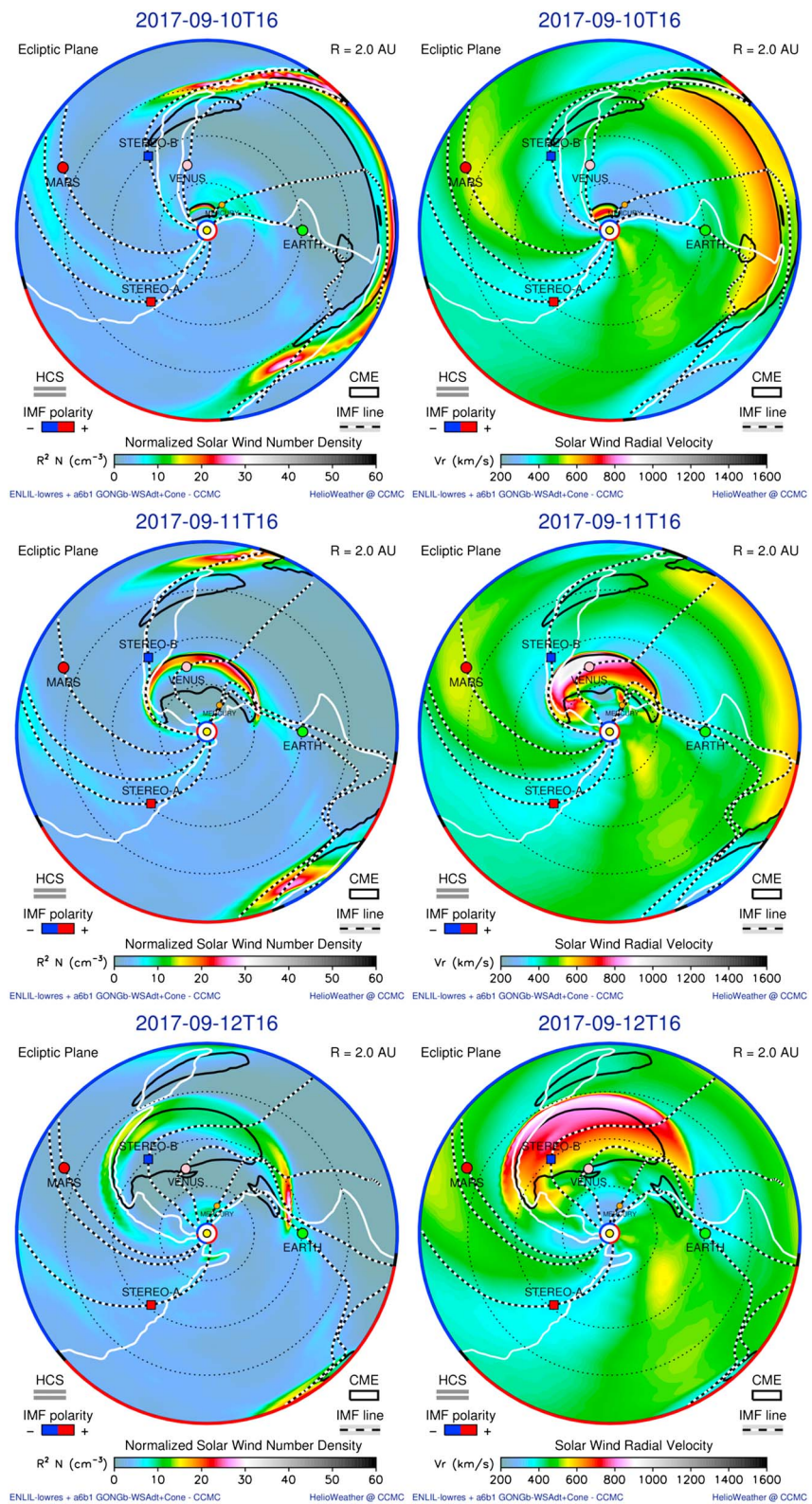
**Figure 8.** In situ plasma signatures of the interplanetary coronal mass ejection (ICME) and magnetic ejecta (ME) observed on 7 and 8 September. Pink vertical lines indicate the ICME start time, the ICME ME start time, and the ICME end time. The panels (top to bottom) correspond to the solar wind magnetic field strength and radial-tangential-normal coordinate system components, density, speed, temperature, plasma beta, and Alfvén Mach number.

form of accumulated dose versus shielding plotted in Figure 5 allows us to estimate the effective shielding (in  $\text{g}/\text{cm}^2$ ) for each of the CRaTER detector pairs. The shielding estimates are roughly consistent with the average shielding provided by the TEP, endcaps, and the side-shielding that encircles all six detectors. These effective shielding depths will be useful in estimating the effects of shielding and the attenuation of dose within materials of varying thickness.

These CRaTER shielding estimates for detector pairs are roughly consistent with the shielding associated with the TEP and endcaps. However, radiation penetrates CRaTER from all directions not blocked by the Moon. For example, the endcap provides  $0.22 \text{ g}/\text{cm}^2$  Al shielding. However, we find effective D1-D2 shielding of  $0.37 \pm 0.02 \text{ g}/\text{cm}^2$ , which is in excess of the endcap shielding due to extra mass around the detector pair and increased shielding from side-penetrating radiation.

An important question is the degree to which the September 2017 could have significant health effects for astronauts. We find from Figure 5 that the lens and skin dose on the lunar surface would approach the 30 day limits ( $100 \text{ cGy}$  skin dose and  $150 \text{ cGy}$  lens dose) (Cucinotta et al., 2010; NRC, 2008; NCRP, 2000). However, even moderate shielding ( $> 1 \text{ g}/\text{cm}^2$  Al shielding) would reduce the radiation dose below these limits. A question is whether the dose would approach radiation limits during an extravehicular activity (EVA), typically lasting  $\sim 3 \text{ h}$ . At the peak skin/lens dose rate of  $5.8 \pm 0.3 \text{ cGy}/\text{h}$  behind  $0.3 \text{ g}/\text{cm}^2$  Al shielding, an astronaut would collect  $17.4 \pm 0.9 \text{ cGy}$  dose within 3 h, which is significantly lower than lens/skin dose limits. This dose and dose rate would be approximately doubled in free space, also below the 30 day limits. Both the accumulated doses during the September 2017 event and the maximum dose rate are significantly smaller than those in extreme SEP events, such as the August 1972 event. For example, the skin dose and maximum skin dose rate behind thin shielding (Al  $0.3 \text{ g}/\text{cm}^2$ ) during the August 1972 event was  $3215 \text{ cGy}$  and  $980.90 \text{ cGy}/\text{h}$  (Hu et al., 2009), more than a decade larger than observed in the September 2017 event.

The precise biological effects of SEP radiation remains an area of active research (e.g., Cucinotta & Durante, 2006; Cucinotta et al., 2010; Schwadron, Blake, et al., 2014). It is clear that the September 2017 event is dangerous, with doses that are large but not conspicuously above limits defined by the radiation



**Figure 9.** Propagation of interplanetary coronal mass ejections (ICMEs) from 10 September (16:00 UT) to 12 September (16:00 UT) 2017 based on Wang-Sheeley-Argue (WSA)-ENLIL simulations. These ICMEs followed the X8.2 flare event on 10 September. The ICMEs over this period propagate toward the Solar Terrestrial Relations Observatory satellite (STEREO)-B direction, at longitudes more than 90° larger than that of Earth. These runs were performed by the Community Coordinated Modeling Center (CCMC).

biology community. An event of this kind represents an example in which astronauts would ideally be located behind the safety of spacecraft shielding. As such, advance warning for such events remains an imperative.

We conclude this section by noting that the accumulated dose in the September 2017 SEP event approached 30 day limits for low shielding thickness. The analysis demonstrates that the hard spectrum substantiated a radiation hazard. The fact that the event arose during a period of relatively quiet solar activity, while not uncommon for the declining phase, suggests that these events may be difficult to predict. However, as discussed in the next section, the event shows an evolution generally consistent with twin-CME scenarios studied by Li et al. (2012) and Lugaz et al. (2017).

## 5. Successive CMEs in Development of the September 2017 SEP Events

The detailed evolution of the SEP events in September 2017 are shown in Figure 6. These include two X-class flares that started each of the major events on 6 and 10 September. Note that the multiple eruptions of the same active region at the Sun created a energetic particle seed population that was subsequently accelerated in the 10 September event, similar to twin-CME scenarios studied by Li et al. (2012) and Lugaz et al. (2017).

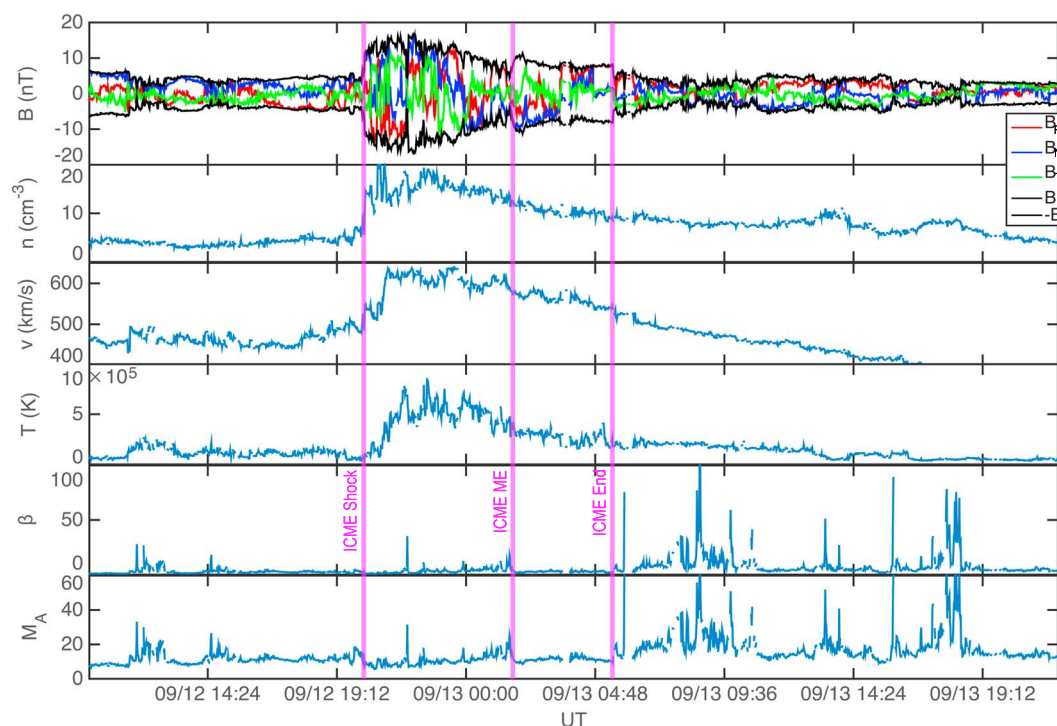
Both of the X-class flares in September were associated with large and fast interplanetary coronal mass ejections (ICMEs). Figure 7 shows the Wang-Sheeley-Argue (WSA)-ENLIL model (Odstrcil et al., 2005) with cone extension for simulating propagation of ICMEs. The simulations were run at the Community Coordinated Modeling Center, with the run *Leila\_Mays\_101017\_SH\_5* and model version number ENLIL 2.8. The model input parameters for the ICME are as follows: latitude =  $-15^\circ$ , longitude =  $24^\circ$ , half-width =  $50^\circ$  speed = 1,850 km/s, and a CME leading edge time of 6 September 2017 at 14:00 UT at the ENLIL inner boundary of 21.5 Rs. For the second ICME the model input parameters are: latitude =  $-10^\circ$ , longitude =  $92^\circ$ , half-width =  $70^\circ$ , speed = 2,800 km/s, and a CME leading edge time of 10 September 2017 at 17:12 UT at the ENLIL inner boundary of 21.5 Rs. Left panels in Figure 7 show simulated density in the ecliptic plane from 6 to 8 September 2017 during the first of the major ICME events. The density enhancement in front of the black contour represents the piled up ICME sheath material. Right panels in Figure 7 show simulated plasma speed in the ecliptic plane. In this case we observe a fast ICME driving a strong compression that presumably forms a shock that sweeps over Earth near 8 September 2017. Note that the modeled fast wind driving the shock that sweeps over Earth has a speed exceeding 900 km/s.

Figure 8 shows the 1 au plasma signatures observed by ACE at 1 au during the passage of the ICME released after the 6 September X9.3 flare. We show (pink vertical lines) the ICME start time, the ICME magnetic ejecta (ME) start time, and the ICME end time. The magnetic field and plasma velocity both show the passage of a shock near the beginning of 8 September 2017. The maximum plasma speed is observed slightly in excess of 800 km/s. At the ME start time to, there is a decrease in magnetic variability and a clear rotation in the magnetic field. Around the same place where ME starts there is also a decrease in temperature and the steady decrease in plasma speed. This ICME was directed at Earth, so we observe the ME.

Trailing behind the ICME is a rarefaction region where the density becomes low ( $> 0.23 \text{ cm}^{-3}$ ), while the magnetic field strength remains close to nominal. As a result, the Alfvén speed becomes large and the Alfvénic Mach number becomes relatively low,  $> 1.3$ . Even lower densities and Alfvénic Mach numbers may be obscured by several data gaps: ACE data gap from 9 September at 01:30 to 11 September at 00:00 and Wind data gap from 10 September at 03:00 to 11 September at 00:00. These conditions are reminiscent of density anomaly observed in May 1999 (Usmanov et al., 2000). Analysis of this rarefaction region is ongoing.

The WSA-ENLIL simulation of the ICME released after the 10 September flare is shown in Figure 9. The WSA-ENLIL model runs from 10 September 2017 to 12 September 2017 show the propagation of the CME from the Sun to 1 au. This second large ICME was directed much closer to the Solar Terrestrial Relations Observatory satellite-B direction, at longitudes more than  $90^\circ$  larger than that of Earth. Only a small portion of the modeled sheath of the ICME sweeps past Earth.

The ICME sheath appears well connected to Earth throughout the propagation of the CME from the Sun to 1 au. This indicates that the energetic particles accelerated from the CME sheath can propagate to Earth throughout the period in which the ICME propagates to 1 au. The in situ plasma signatures observed at 1 au (Figure 10) also show evidence of the compressed ICME sheath and ME; however, both structures are significantly smaller and weaker than in the ICME observed on 8 September.



**Figure 10.** In situ plasma signatures of the interplanetary coronal mass ejection (ICME) and magnetic ejecta (ME) observed on 12 and 13 September. Pink vertical lines indicate the ICME start time, the ICME ME start time, and the ICME end time. The panels (top to bottom) correspond to the solar wind magnetic field strength and radial-tangential-normal coordinate system components, density, speed, temperature, plasma beta, and Alfvén Mach number.

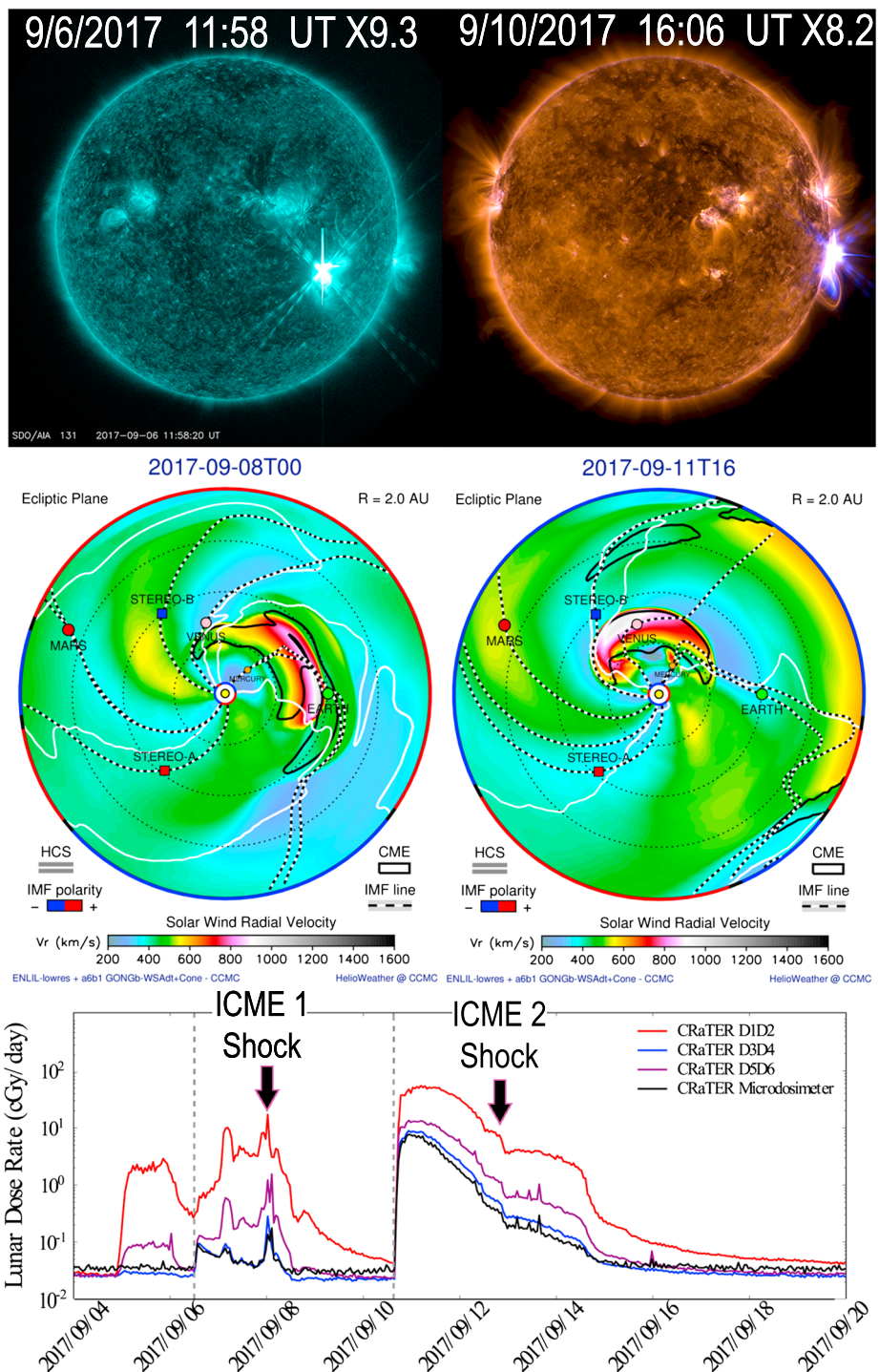
A key question is how large events such as the 10 September 2017 event arise. The answer must take into account many factors including (1) the size, speed, and shock or compression characteristics of the CME and ICME driver; (2) the magnetic connectivity throughout the event (e.g., Schwadron et al., 2015), and (3) the existence of suprathermal seed populations (e.g., Desai et al., 2003, 2006; Schwadron et al., 1996).

The case observed appears to have all the ingredients necessary for extremely high-energy particle acceleration: (1) the CMEs released on 6 and 10 September were large and fast (speeds > 600 km/s); (2) there was direct magnetic connectivity between the CME shock or compression and Earth throughout the propagation of both events; (3) the first of the CME events created a large energetic particle seed population accelerated further during the passage of the second CME (consistent with the twin-CME scenario Li et al., 2012); and (4) we are well connected to the flank of the second ICME, where the shock is quasi-perpendicular, which is likely more efficient for particle acceleration (e.g., Schwadron et al., 2015).

Figure 11 summarizes the successive CME events causing particle acceleration to high energies. The first 6 September event showed the clear signature of enhanced energetic storm particles (ESP) accelerated by the shock during the passage of the Earth-directed ICME. In contrast, the second ICME showed only a small ESP enhancement near 12 September at 20:00 UT during passage of the ICME shock. In fact, the peak fluxes occurred when the CME was relatively close to the Sun.

The observed acceleration by successive ICMEs is well known to be a powerful energetic particle accelerator (Gopalswamy et al., 2004; Li et al., 2012; Lugaz et al., 2017). The first CME causes enhancements in energetic particles throughout the inner heliosphere. In fact, prior to the beginning of the 10 September event, we observe energetic particle enhancements up to at least 30 MeV. Further, throughout the event we continue to see the more rapid decay of energetic particles above 30 MeV after the passage of the ICME shock near the beginning of 8 September 2017, suggesting that energetic particles continue to diffuse out from the region inside of 1 au. During the acceleration of the second CME, an energetic particle population already exists,

## Successive CMEs Causing Acceleration of High Energy SEPs directed near the Earth & Moon



**Figure 11.** Summary of observations of the 6 and 10 September solar energetic particle (SEP) events. We note that the 6 September event resulted in a coronal mass ejection (CME) directed toward Earth, whereas the 10 September CME was directed 90° longitudinally forward. As a result, the first Earth-directed event showed the passage of the CME and the associated shock, and the energetic storm particles (ESP) accelerated in interplanetary space. In contrast, the 10 September SEP event did not show a pronounced shock-associated ESP enhancement in energetic particles.

which then significantly increases the seed population fed into acceleration. This appears to be a scenario ideal for acceleration from the flanks of the second expanding and accelerating CME close to the Sun (Schwadron et al., 2015).

## 6. Summary and Conclusions

We have shown that there has been a rapid GCR recovery in the approach to solar minimum over the period from 2014 to 2017. Previously, Schwadron, Blake, et al. (2014) studied the evolution of GCR dose rate through solar cycles throughout the space age, concluding that the coming solar minimum will show increased fluxes and dose rates associated with GCRs compared to previous minima. GCR dose rates are increasing at a rate faster than predicted by Schwadron, Blake, et al. (2014).

Despite the low solar activity of cycle 24 and the continued weakening of solar activity in the descending phase, we have observed a relatively large SEP event in September of 2017. The event appeared as the result of successive fast CMEs, the first released on 6 September 2017 directed at Earth and the second released on 10 September 2017 directed  $>90^\circ$  longitudinally forward with respect to Earth. Both events were magnetically well connected, but the enhanced energetic particle populations accelerated in the first event were subsequently accelerated in the second CME event. These observations provide strong support for particle acceleration by successive ICMEs (Gopalswamy et al., 2004; Li et al., 2012; Lugaz et al., 2017).

We conclude that we are likely in an era of decreasing solar activity. The activity is weaker than observed in the descending phases of previous cycles within the space age and even weaker than the predictions by Schwadron, Blake, et al. (2014). We continue to observe large but isolated SEP events, the latest one occurring in September of 2017 caused largely by particle acceleration from successive magnetically well-connected CMEs. The radiation environment remains a critical factor with significant hazards associated both with historically large GCR fluxes and large but isolated SEP events.

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